

AD-A076 770 PENNSYLVANIA STATE UNIV UNIVERSITY PARK APPLIED RESE--ETC F/G 14/5
X-RAY BACKSCATTER IMAGING.(U)

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energy x-ray machines.

The x-ray dose received by a backscatter radiographed object is significantly less than that needed to create a conventional radiograph. This is especially important in medicine where several backscatter examinations can be conducted for a dose level less than a single conventional examination.

The ultimate practicality of this system cannot yet be judged. The cost of any new imaging device must be justified by its effectiveness in diagnosis. Also a broad area of application would be necessary to offset the expense of an additional x-ray imaging technique.

The next logical step in this research is to evaluate the system in a clinical environment to see if the backscatter technique will produce images of diagnostic significance. This requires both medical and engineering expertise to properly evaluate a possible new imaging system.

APPENDIX A

X-RAY TUBE CONSTRUCTION

Construction of the fast scanning x-ray tube was accomplished by modifying an RCA 71P4 cathode ray tube. This tube is 7 inches in diameter and is designed to withstand high voltages on the accelerator anode. The tube is of double envelope construction to prevent high voltage arc over through the glass. This tube was originally intended to project high brightness television pictures onto auditorium screens, and so was designed for high power operation.

The modification to the tube consists of cutting off the faceplate by heating till fracture along a scribe mark, then replacing the original tube luminescent screen with a tungsten plate. The tungsten plate is .25mm thick and mounted on a copper heat sink with cooling coils used to dissipate target heat.

A new tube front extension was created by the glassworking shop. It incorporated kovar-to-glass vacuum seals to allow copper cooling coils to pass in and out of the vacuum. A high vacuum valve was used to seal off the tube from the vacuum system, and a beryllium x-ray window was sealed on the front for transmission targets.

The new tungsten target was 5 inches square and tilted 45 degrees to the electron beam incidence. The generated x-rays passed through the side of the 3/16" pyrex glass tube front extension, 90 degrees to the electron beam incidence on the target.

The tube front extension was attached to the rest of the tube by epoxy, rather than by glass sealing the two sections together to allow disassembly of the tube by burning off the epoxy. The epoxy was found vacuum stable after it had been heated and thoroughly outgassed. This formed a vacuum tight seal which did not deteriorate under x-ray bombardment.

A roughing pump and 10 liter/second diffusion pump were used to exhaust the tube to an ultimate pressure of 2×10^{-7} TORR, tube quiescent, to 3×10^{-6} TORR, tube operating. The target and glass inside the tube continued to outgas even after many hours of operation, reducing the ultimate vacuum obtainable. Commercial sealed off vacuum tubes are baked at 400 degrees Celsius to rid absorbed gasses in the metal and glass. This was not practical with the demountable laboratory tube.

High voltage was supplied by a DEL electronics 130 kilovolt, 2 milliamp DC supply. Other tube control voltages were applied through the tube base pins. A problem developed when the tube was powered up for operation. The electron gun incorporates an oxide cathode to generate free electrons for the beam current. The cathode is a disk coated with barium and strontium salts which, when heated, lowers the work function of the cathode surface so that electron emission can occur at low thermal temperatures. When the tube is opened to an atmosphere, the active electronegative monolayer is poisoned by oxygen and ceases to emit electrons, resulting in no beam current (Jenkins and Trodden, 1959).

Vapors released by the diffusion pump due to slight decomposition, of the fluid during operation, also tend to poison the cathode. This problem was solved by placing an alumina trap in the diffusion pump line. This worked satisfactorily in stopping cathode poisoning from this source (Bondi, 1959).

Several hours of continual operation at saturated beam current gradually causes the cathode to rejuvenate, but to a lower level than when new. Beam currents of up to 1 milliamp could be achieved to create

backscatter images with this tube. This current level could only be reached by operating the cathode at an elevated temperature. Demountable tubes usually do not use oxide filaments, choosing instead tungsten filaments, which do not poison but have shorter life.

A transmission target was initially tried in the tube. The x-rays produced with this type of target, transmit through the target metal and pass out through the front of the tube. The advantage of this configuration is that electron beam focusing is easier than using a tilted reflection target. It also has geometric factors in its favor. The beam intensity at the output aperture changes more in a reflection target since the target to aperture distance variation is greater. The reflection target was used because of its higher x-ray output. The tube power is limited by the vacuum achievable during operation. This restricts the high voltage that can be applied to the tube without internal arc over between the elements.

Magnetic deflection of the electron beam was accomplished by driving a special deflection coil made by CELCO INC. The raster generator supplied the current to the deflection coil through 10 ampere power amplifiers. The available amplifiers were only capable of driving the horizontal scan at 4kHz. This means that a maximum scan rate is about 8 frames per second for a 128 line image. Higher framing rates could be attained if fewer scan lines are needed.

The x-ray tube was enclosed in an 3" lead lined pipe which was capped at either end. A cutout in the back allowed coolant and vacuum connections. The x-ray beam passes out through a small lead aperture, typically 1mm to 2mm in diameter, on the side of the tube. It diverges to cover a 4 inch square area about 5 inches away from the shield body.

A simple geometric relationship holds for the area of target scanned to the raster size at any distance from the aperture:

$$R=(R_1/R_2)L$$

where R is the raster linear dimension at the object plane, R_1 is the pinhole to object distance, R_2 is the target to pinhole distance, and L is the target linear dimension.

The scintillation detectors for the project were made from parts because commercial detectors of the required area versus thickness were difficult to find. Scintillation detectors were constructed from thallium activated sodium iodide crystal blanks purchased from Harshaw Scientific Co. The crystals were coupled to EMI 9778bialkali cathode photomultiplier tubes. The crystals were 1/2" thick by 3" square and were encased with x-ray transparent beryllium metal windows on the crystal face. The scintillator crystals were thick enough so that they essentially were 100% efficient in stopping and detecting x-rays in the energy range used. The detector response to x-radiation is linear and the photomultiplier tubes provide high gain at very low noise.

APPENDIX B

X-RAY GENERATION

X-rays are generated by bombarding a metal target with high speed electrons. A spectrum of radiation is produced extending from zero electron volts up to the accelerating potential applied to the tube. The x-ray spectral distribution toward the low energies is partly a result of high speed electrons suddenly decelerating around the nucleus of an atom with radiation of longer wavelengths given off. This radiation is called Bremsstrahlung or braking radiation and is mainly responsible for the wide spectrum of x-ray machines.

Characteristic radiation from the target material contributes to high intensity spectral peaks. The mean or effective energy of the x-radiation is considerably below the accelerating potential of the tube. The effective energy is often taken as one half the potential applied to the tube.

Beam filtration by thin pieces of metal can raise the mean effective energy by stopping the lower components of the beam. Some high energy photons are stopped in the process but in a lower proportion than the low energy flux.

The generation of x-rays is a very inefficient process. Less than one percent of the total power consumed is given off as x-rays. The rest is dissipated as heat. The efficiency of x-ray production goes up with accelerating voltage and atomic number of the target. The amount of x-ray flux generated is

$$R = KV^2IZ,$$

where R is the photon flux in units of Roentgens per minute, K is a constant, V is the tube accelerating voltage, I is the tube anode current, and Z is the atomic number of the target.

APPENDIX C

PHOTON STATISTICS

The factor which, at present, limits the resolution is the increase in image noise with small beam apertures. The quantum nature of electromagnetic radiation means that its generation as well as its detection is statistical in nature. The x-ray backscatter scintillation detectors generate individual electrical pulses corresponding to x-ray photon detection. An image is composed of millions of detected photon events. The uncertainty or standard deviation in a random process due to statistical considerations is proportional to the inverse square root of the number of photon events (N) comprising that level:

$$\sigma = \frac{1}{\sqrt{N}} \quad .$$

The statistical deviations from a uniform gray scale are specified by a signal-to-noise ratio (SNR). In an image point, the signal is defined as the mean particle count N in an image point I and the noise amplitude is the root mean square deviation from the mean count. The number of photons which scatter from deep in the object are less than those scattering from near the surface so the noise in the resulting image increases with penetration depth.

For a photon count N per image point, the signal to noise ratio (SNR) is written:

$$\text{SNR} = N^{.5} \quad .$$

It is necessary to have as large as possible number of detected photon events per picture element (pixel) to achieve the highest quality image with the lowest noise. The resolvable contrast levels of subtle details in the image likewise is dependent on the noise uncertainty. If for example 100 photon events comprise a pixel, the

noise uncertainty is 10%. Smaller changes than this in the contrast of the image element are not resolvable due to the larger statistical variation in the detection process.

A backscatter image of 256 lines by 256 points per line with 10 percent noise uncertainty requires a total of 6.5×10^6 photon events comprising the image. This is about the noise level of some of the relatively deep penetration backscatter radiographs. A noise uncertainty of ten times less (1 percent), however, requires a hundred times more photons, 6.5×10^8 . This noise level is very good and roughly the same as a 35mm camera picture but at lesser resolution.

The number of detected events in backscatter imaging is dependent on the intensity of incident beam flux, which is in turn dependent on the beam aperture diameter and collimation. The x-ray flux passing through an aperture is proportional to the square of its diameter. The signal to noise ratio changes as the square root of the flux so the picture quality improves in direct proportion to the aperture diameter.

In a scanning process, the number of photons in each image element is dependent on how long the incident beam dwells on the element. Longer dwell times increase photon statistics for that point and reduce the noise level. This results in a longer time to create the image. The main factor in the quality of a backscatter image is the practical limitation in scanning time. The image noise can be decreased by trading off resolution, or scanning time.

The ultimate resolution is governed, to some extent, by the brightness of the x-ray source. This refers to the maximum loading in watts/mm² and is not the same as the maximum tube power dissipation. The x-rays generated by a focal spot larger than the area intercepted by

the beam collimator are wasted since they are not parallel to the collimator port and do not energy through the aperture.

X-ray tubes concentrate all power into the smallest possible spot. The limitation is the melting of the x-ray target. Typical fixed target x-ray tubes have loadings of about 100 watts/mm^2 . The power loading does not change much with higher power x-ray machines, the focal spot just tends to get larger.

Rotating anode x-ray tubes have a target which is a spinning disk. This spreads the heat over a larger area and permits loadings up to 1 kilowatt/ mm^2 . The x-ray machine used in this research had a focal spot of 2mm by 3mm with a maximum loading of 600 watts continuous duty, ie., about the maximum loading of 100 watts/mm^2 for fixed anode machines. With this loading, it was found that beam apertures much smaller than about 1mm took too long to create an image at a reasonable noise level. A rotating anode x-ray tube has a distinct advantage in power loading. The problem is that these tubes are intermittent duty, and continuous power dissipation is not much larger than the fixed anode tubes.

Higher energy x-ray machines (300 KVP) are more efficient at producing x-ray flux and therefore have greater intensities for a given power dissipation.

APPENDIX D

BANDWIDTH

The bandwidth of an image refers to the range of frequencies present in the analog image signal. A completely grey image contains only DC information, while an object with high spatial frequencies will be translated into a signal with high analog frequencies by the scanning process. The bandwidth of the resulting analog signal depends on the number of image elements divided by the total scan time. In these experiments, typical scan times of five to twenty minutes were used to scan a 4" by 4" object, using a one millimeter beam collimator. This results in about a 100 pixel square picture (10,000 pixels) created in about 600 seconds. The bandwidth of the resulting analog signal goes from dc to 16HZ.

The analog system must be able to pass these frequency signals. Knowing the highest frequency analog signal of interest allows the use of low pass filtering to suppress noise and unwanted high frequency interference.

A real time x-ray scanner, ie. one that creates a backscatter image at a TV frame rate of 30 images per second, has a very large bandwidth. A standard TV image has about 500 lines with 500 points per line (250,000 pixels), generated in 66 milliseconds (interlaced) for a bandwidth of 4 Mhz. The beam dwell time on each point is correspondingly small, .12 microseconds compared to the x-ray mechanical imaging system dwell of 62 milliseconds.

Several problems arise for real time backscatter imaging. The biggest problem is the large increase in flux that is required to maintain reasonable photon statistics. Another problem is that the detectors must be fast enough to keep up with the data rate.

Sodium iodide scintillation crystals are the most efficient detector of x-rays, but have a relatively slow (.25 microsecond) response time. Plastic scintillator crystals have nanosecond response time but are relatively poor detectors of x-rays. This problem can be solved by reducing the number of scan lines in half, or reducing the frame rate to 15 frames per second.

The large increase in flux required is a formidable problem with the present x-ray generator technology. Photon noise will be high in any backscatter image made in milliseconds. Noisy images may be tolerable though, if diagnostic information can be extracted from them. Most backscatter imaging, except for special applications, requires seconds to several minutes to create a good quality image.

APPENDIX E

MULTIPLE SCATTERING

High energy radiation can undergo many scatterings before absorption in the material. Photons that scatter into other parts of the object, and then scatter back into the detector, cause an error in the density measurement of the desired point. This is because some of the photons have scattered from other areas whose density may be different.

Multiple scattering has been a problem in gamma ray scattering densitometry, often limiting measurement precision to within ten percent. Collimation of the detector, so that it views only a small portion of the object under study, reduces detected multiple scatter at the expense of lower photon statistics and higher dose rates.

Multiple scatter has not been a serious problem in x-ray backscatter imaging. This is probably attributable to the lower energies employed compared to gamma ray techniques. Lower energy photons will on the average scatter a fewer number of times before absorption. It appears that with the 50 to 150 KVP range of energies used, single scatter is by far the dominant interaction.

Collimation of the detector was tried in this work, but it did not substantially increase the quality of any of the images. Collimation actually tended to degrade the image by reduction of photon statistics.

APPENDIX F

NON-DESTRUCTIVE TESTING

The techniques presented throughout this research can be applied to imaging as used in nondestructive testing and quality control. The principal application is probably to those situations which cannot be radiographed at present because of limited rear access.

One common use for backscatter radiography would be to radiograph welds from one side. Backscatter imaging has the advantages of ultrasound with respect to one sided access. Radiography, however, is not hampered by large voids or spaces in the material which can prevent an ultrasound examination.

Figure 31a shows a 6" long T weld on 1/4" aluminum plate. Holes were drilled up through the weld from the bottom to various depths from the surface. This was to simulate defects in the weld. Figure 31b shows a backscatter image of the welded T looking into it from the weld surface. The dark spots in the radiograph are regions of lower scatter resulting from the simulated "defects" in the weld. Other radiographs made in this research show what might be expected in terms of resolution and penetration depth in aluminum.

Significant penetration in dense materials such as iron requires higher photon energies. The x-ray machine used in this research could not scatter image through even 1/8" iron. An iridium-192 gamma ray isotope, which has a mean energy of about 400 KEV, was substituted for the x-ray machine to attempt backscatter imaging through iron. This radioactive isotope is commonly used in industry to radiograph 1/2" thick steel materials. The available source had an activity of only 200 millicuries, about ten to a hundred times weaker than available in

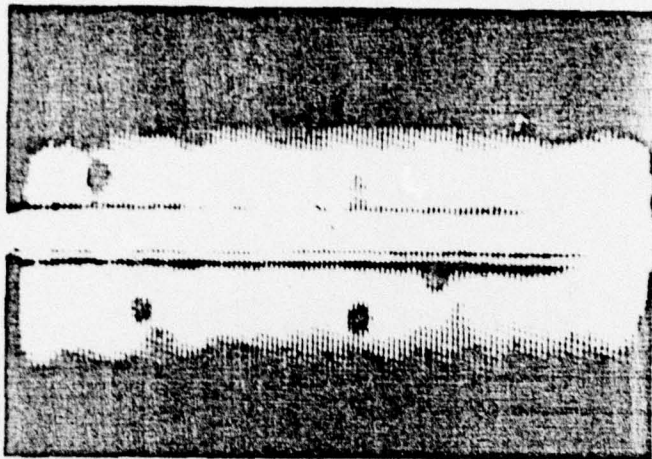
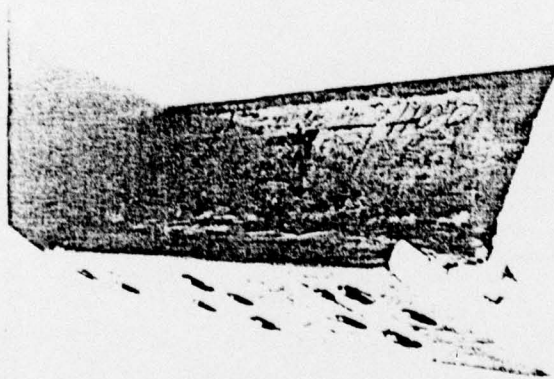
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Fig. 31. Backscatter Imaging of Welds;
a) Backscatter Image of Welded Aluminum 'T' Joint
Seen Looking into Weld from the Top,
b) Photograph of Welded 'T' Joint Seen from End.

industry. The backscatter images produced were necessarily of much lower quality than possible to attain with higher flux sources. The source was used with a 2-3mm beam collimator to improve photon statistics at the expense of resolution.

Figure 32a shows an 8" long adjustable wrench beneath a $3/16$ " steel plate. This object was selected principally to demonstrate the feasibility of industrial backscatter imaging. Three-sixteenths of an inch is near the maximum imaging depth possible with this experimental setup. Imaging depths up to $3/8$ " in steel should be feasible with more intense iridium sources. Figure 32b shows the test object with the steel shield turned over.

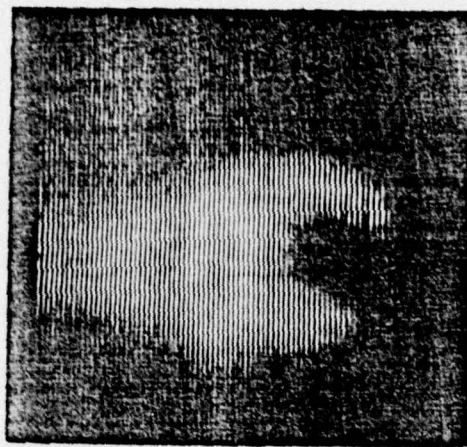
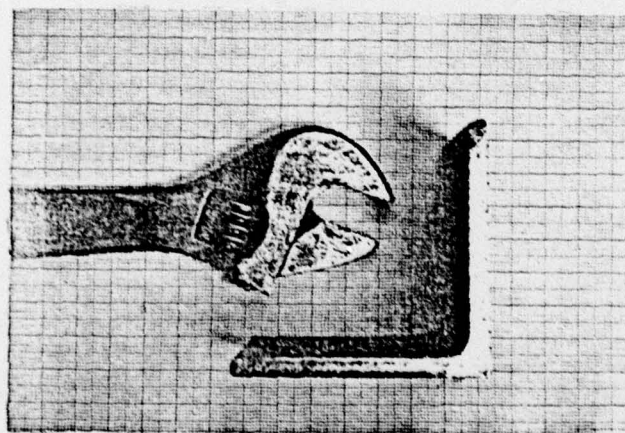
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Fig. 32. Gamma Ray Backscatter Imaging;
a) Backscatter Image of a Wrench Beneath a 3/16" Steel Plate
Using an Iridium-192 Gamma Source,
b) Photograph of Wrench with the Steel Plate Rotated on End.

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